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Light Scalar Top and Heavy Top Signature at CDF

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We propose a mechanism which could explain a slight excess of top signal rate recently reported by CDF in the framework of the supersymmetric standard model. If the scalar partner of the top (stop) is sufficiently light, the gluino with an appropriate mass could decay into the stop plus the top with almost 100% branching ratio and experimental signatures of the gluino pair production could be indistinguishable from those of the top production in the present integrated luminosity Tevatron running. In this case the standard top signal, W + multi-jets events, would be effectively enhanced by the additional gluino contribution. It is shown, moreover, that such a mechanism can actually work in the radiative SU(2)×U(1) breaking model without the GUT relations between the gaugino mass parameters.

The CDF experiment at the Fermilab Tevatron $p\bar{p}$ collider has recently reported the first evidence for a top quark signal, indicating a mass $m_t = 174 \pm 10^{+13}_{-12}$ GeV [1]. They have found an excess of W + multi-jets events containing at least one b-jet, where the W is identified by $W \to \ell\nu$ decay. The observed signal rate ($\sigma_{t\bar{t}} = 13.9\ ^{+6.1}_{-4.8}$ pb [1]) is slightly higher than those expected from the standard $p\bar{p} \to t\bar{t}X$ cross section [2]. Although this higher rate may be attributed to statistical fluctuations or background uncertainties, some mechanisms have already been proposed to explain this discrepancy [3–5]. In this letter we present another mechanism which could explain such a higher top signal rate in the framework of the supersymmetric (SUSY) standard model [6].

In the framework of SUSY standard model with minimal contents of ordinary particles and their SUSY partners [6], a large cross section of the gluino $\widetilde{g}$ pair production in $p\bar{p}$ collisions is expected because the production occurs via the QCD interaction [7]. Two types of sub-processes contribute to the production, i.e., the gluon-gluon fusion $gg \to \widetilde{g}\widetilde{g}$ and the quark-antiquark scattering $q\bar{q} \to \widetilde{g}\widetilde{g}$. The latter contains the squark exchange diagrams and

in turn those contributions depend on squark masses $m_{\widetilde{q}}$. In Fig. 1 we show the gluino mass $m_{\widetilde{g}}$ dependence of the total cross section at Tevatron $\sqrt{s}$ = 1.8TeV. It should be noted that the cross section increases as $m_{\widetilde{q}}$ increases [8]. This is due to a reduction of destructive interference between the production diagrams involving initial-state quarks. We can obtain the total cross section $\sigma \simeq 5$ pb for $m_{\widetilde{g}} \simeq 180$GeV [200GeV] when $m_{\widetilde{q}} = 0.3$TeV [1TeV]. Note that $\sigma \simeq$5pb is almost the same value with the total cross section of $p\bar{p} \to t\bar{t}X$ for $m_t \simeq 170$GeV expected by the standard QCD [2].

Searches for the gluino with large $\not{E}_T$ signature have been performed at CDF [9] and D0 [10] and negative results have been used to set the lower mass bounds such as $m_{\widetilde{g}} \gtrsim 100$GeV for $m_{\widetilde{g}} \leq m_{\widetilde{q}}$. In those analyses the cascade decays $\widetilde{g} \to q\bar{q}\widetilde{Z}_{2,3,4}$ and $\widetilde{g} \to ud\widetilde{W}_{1,2}$ as well as the direct decay $\widetilde{g} \to q\bar{q}\widetilde{Z}_1$ have been taken into account [8,11].

Here we consider the case $m_t + m_{\widetilde{t}_1} < m_{\widetilde{g}} < m_{\widetilde{q}}$, where $\widetilde{t}_1$ and $\widetilde{q}$ respectively denote the lighter scalar partner of the top (stop) [12,13] and all the other squarks. Then the two-body decay mode [14]

$$\widetilde{g} \to t\widetilde{t}_1^*,\ \bar{t}\widetilde{t}_1 \tag{1}$$

will dominate over the conventional three-body decay modes. We assume that (i) the stop has a small mass and the dominant decay mode $\widetilde{t}_1 \to c\widetilde{Z}_1$ [13] and almost degenerates in mass with the lightest neutralino $m_{\widetilde{t}_1} \gtrsim m_{\widetilde{Z}_1}$ and (ii) the top decays dominantly into bW [15]. In this case experimental signatures of the gluino pair production $p\bar{p} \to \widetilde{g}\widetilde{g}X \to t\bar{t}\widetilde{t}_1\widetilde{t}_1^*X$ will resemble to the standard top signal because the transverse momentum of the charm-jets from the final stops will be too soft to be detected. Moreover, if the gluino mass is smaller than about 200GeV, the top (like) signal rate will be effectively enhanced since $\sigma(p\bar{p} \to \widetilde{g}\widetilde{g}X) \simeq \sigma(p\bar{p} \to t\bar{t}X)$ as mentioned above. That is, the slight excess of the top signal rate at CDF could be explained by such an additional gluino contribution. Note that it is required that the stop should be sufficiently light $m_{\widetilde{t}_1} \lesssim 30$GeV, owing to the conditions, $m_{\widetilde{t}_1} < m_{\widetilde{g}} - m_t$, $m_{\widetilde{g}} \lesssim 200$GeV and $m_t \sim 170$GeV.

In Fig. 2 we show various event distributions for the processes $p\bar{p} \to \widetilde{g}\widetilde{g}X \to t\widetilde{t}_1X \to bWX \to b\ell X$ and $p\bar{p} \to t\bar{t}X \to bWX \to b\ell X$, where we take $m_t = 170$GeV, $m_{\widetilde{g}} = 190$GeV, $m_{\widetilde{q}} = 350$GeV, $m_{\widetilde{t}_1} = 15$GeV and $m_{\widetilde{Z}_1} = 13$GeV. We can find that it would be difficult for us to distigush the gluino events from the standard top events in the present integrated luminosity $L = 19.3\text{pb}^{-1}$ Tevatron running [1]. It is worth mentioning that higher statistics will enable us to confirm or reject our scenario. Since the gluino can decay into both final states $t\widetilde{t}_1^*$ and $\bar{t}\widetilde{t}_1$ due to its Majorana nature, like sign W-boson pairs, i.e., like sign lepton pairs will be expected in the final state of $p\bar{p} \to \widetilde{g}\widetilde{g}X$ with an equal event rate to opposite sign lepton pairs.

Next we should examine a possibility for the existence of a very light stop $m_{\widetilde{t}_1} \lesssim 30$GeV and a light neutralino $m_{\widetilde{Z}_1} \lesssim m_{\widetilde{t}_1}$ [16,17]. Difficulties in the possible detection of such a light stop through the direct searches $p\bar{p} \to \widetilde{t}_1\widetilde{t}_1^*X$ at Tevatron [14,18] as well as through the measurement of the extra decay width of Z-boson $\Gamma(Z \to \widetilde{t}_1\widetilde{t}_1^*)$ at LEP [19] have already been pointed out. Okada [20] has investigated possible bounds on masses of the stop and the neutralino from the experimental data of the $b \to s\gamma$ decay. He has shown that the light stop with mass $m_{\widetilde{t}_1} \lesssim 20$GeV has not been excluded by the data. It has been also pointed out by Fukugita et al. [21] that the existence of the light stop does not conflict with the

experimental bounds on $\Delta\rho$ and $K^0 - \bar{K}^0$ mixing. Recently, severe limits come from the direct searches for the stop at e^+e^- colliders [22–24]. In particular, OPAL group [23] has shown the light stop $m_{\widetilde{t}_1} < m_Z/2$ survives only if $m_{\widetilde{t}_1} - m_{\widetilde{Z}_1} < 2.2$GeV and $0.85 < \theta_t < 1.15$, where θ_t denotes the mixing angle of stops [13,19].

It should be remarked that there is a possible sign of the existence of a light stop. Recently Enomoto et al. in the TOPAZ group at TRISTAN have reported a slight excess of the high p_T cross section of $D^{*\pm}$-meson production in a two-photon process [25]. The disagreement between the measured value and the standard model prediction becomes 3.5σ level [26]. Although there remains a possibility that such a excess could be explained by the large contribution of the gluonic structure of the photon [27], there is another exciting way to interpret this enhancement, i.e., it is the pair production of the stop with mass $\lesssim$ 20GeV. Since such a light stop will decay into the charm-quark plus the lightest neutralino [13], the signature of the stop production will be the charmed meson production with large missing energies. This signature would resemble the charmed-hadron production in the two-photon process at e^+e^- colliders. Enomoto et al. have pointed out that the stop with mass about $15 \sim 16$GeV and the neutralino with mass about $13 \sim 14$GeV could explain the experimental data [26].

We have examined previously [16,17] such a light stop scenario in the framework of the minimal supergravity GUT model (MSGUT) [28]. It has been emphasized that the existence of the light neutralino $m_{\widetilde{Z}_1} \lesssim 20$GeV inevitably lighten the gluino $m_{\widetilde{g}} \lesssim 100$GeV [29] if we take the GUT relations between the soft gaugino mass parameters at the weak scale,

$$M_1 = \frac{5}{3} \tan^2 \theta_W M_2, \tag{2}$$

$$m_{\widetilde{g}} = M_3 = \frac{\alpha_s}{\alpha} \sin^2 \theta_W M_2, \tag{3}$$

which are related to the boundary conditions for the soft gaugino masses at the GUT scale, $M_3(M_X) = M_2(M_X) = M_1(M_X)$. In this case the gluino can not decay into the stop plus the top and the mechanism giving the higher event rate of the top signal at CDF does not work. However, if we generalize the boundary conditions for the gaugino masses,

$$f_3^{-1} M_3(M_X) = f_2^{-1} M_2(M_X) = f_1^{-1} M_1(M_X), \tag{4}$$

the GUT relations at the weak scale are modified as [17]

$$M_1 = \frac{5}{3} \tan^2 \theta_W \frac{f_1}{f_2} M_2, \tag{5}$$

$$m_{\widetilde{g}} = M_3 = \frac{\alpha_s}{\alpha} \sin^2 \theta_W \frac{f_3}{f_2} M_2, \tag{6}$$

where f_i are arbitrary constant parameters. We can obtain arbitrary large gluino mass taking $f_3/f_2 > 1$.

In Fig. 3 we show contours for $m_{\widetilde{Z}_1} = 13$GeV and $m_{\widetilde{W}_1} = 45$GeV in (μ, $m_{\widetilde{g}}$) plane, where we take $\tan\beta = 3$, $f_2 = 2$ and $f_3 = 2.5$, for example [30]. We can find that $m_{\widetilde{Z}_1} \simeq 13$GeV corresponds to $m_{\widetilde{g}} \simeq 200$GeV for $\mu \lesssim -50$GeV and such a light neutralino has not been excluded by the limit $m_{\widetilde{W}_1} > 45$GeV at LEP in this example. Of course, there is a large

number of parameter sets (f_i, μ, $\tan\beta$, $m_{\widetilde{g}}$) which allow the existence of the heavy gluino $m_{\widetilde{g}} \lesssim 200$GeV and the light neutralino $m_{\widetilde{Z}_1} \lesssim 20$GeV.

We can present, moreover, solutions for the renormalization group equations (RGEs) [31] in the radiative SU(2)×U(1) breaking model, which satisfy all requirements mentioned above as well as the present experimental constraints. The RGEs and their analytical solutions for the general boundary conditions (4) can be found in Appendices A and B in Ref. [17], respectively. In our calculational scheme [33,16,17] all physics at the weak scale m_Z are determined by the six input parameters (f_2, f_3, M_2, μ, $\tan\beta$, m_t). As an example, we take $f_2 = 2$, $f_3 = 2.5$, $M_2 = 42$GeV, $\mu = -336$GeV, $\tan\beta = 3$ and $m_t = 170$GeV [32]. In this case output masses and mixing angles are $m_{\widetilde{g}} = 188$GeV, $m_{\widetilde{t}_1} = 15$GeV, $\theta_t = 1.1$, $m_{\widetilde{q}} = 330$GeV, $m_{\widetilde{\ell}} = 285$GeV, $m_{\widetilde{Z}_1} = 13$GeV, $m_{\widetilde{Z}_2} = 51$GeV, $m_{\widetilde{W}_1} = 51$GeV, $m_h = 79$GeV and $\alpha = -0.36$, where α denotes the Higgs mixing angle [34]. Following properties of the parameter set should be noted.
(i) The gluino can be produced with the cross section $\sigma(p\bar{p} \to \widetilde{g}\widetilde{g}X) \simeq \sigma(p\bar{p} \to t\bar{t}X)$ and can decay into the stop plus the top, $m_{\widetilde{g}} > m_{\widetilde{t}_1} + m_t$.
(ii) Since the stop almost degenerates with the lightest neutralino $m_{\widetilde{t}_1} - m_{\widetilde{Z}_1} < 2.2$GeV, its experimental signal, the charm-jets from $\widetilde{t}_1 \to c\widetilde{Z}_1$ decay, would be difficult to be observed at Tevatron.
(iii) The branching ratios of the top [35,14] are BR$(t \to bW) \simeq 90\%$ and BR$(t \to \widetilde{t}_1\widetilde{Z}_1, \widetilde{t}_1\widetilde{Z}_2)$ $\simeq 10\%$.
(iv) The stop mixing angle $\theta_t = 1.1$ lies in the range $0.85 < \theta_t < 1.15$ and the light stop $m_{\widetilde{t}_1} < m_Z/2$ has not been excluded by the recent direct searches at LEP [23,24] in this case.
(v) Masses of all the other SUSY particles and the Higgs bosons lie in the experimentally allowed range [36–38], where we have included the radiative correction in the calculation of the Higgs masses [39].
Note that the parameter set presented here is an example and there is a large number of parameter sets (f_2, f_3, M_2, μ, $\tan\beta$, m_t) which have similar interesting properties.

In summary, we have proposed a mechanism which could explain a slight excess of top signal rate recently reported by CDF in the framework of the supersymmetric standard model. If the stop is light enough $m_{\widetilde{t}_1} \lesssim 30$GeV, the gluino with mass about 200GeV could decay into the stop plus the heavy top $m_t \simeq 170$GeV with almost 100% branching ratio and experimental signatures of the gluino pair production will be indistinguishable from those of the top production in the present integrated luminosity Tevatron running. In this case the standard top signal, W + multi-jets events, will be effectively enhanced by the additional gluino contribution. It has been shown that such a mechanism could actually work in the radiative SU(2)×U(1) breaking model without the GUT relations between the soft gaugino masses. It shoud be emphasized that higher statistics at Tevatron enables us to confirm or reject our scenario through our searching for like sign lepton pairs with an equal event rate to opposite sign lepton pairs in the final state of the gluino pair production.

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FIGURES

FIG. 1. Gluino mass dependence of total cross section for $p\overline{p} \to \widetilde{g}\widetilde{g}X$ at Tevatron $\sqrt{s} = 1.8$TeV.

FIG. 2. Various event distributions for $p\overline{p} \to \widetilde{g}\widetilde{g}X \to t\widetilde{t}_1X \to bWX \to b\ell X$ and $p\overline{p} \to t\overline{t}X \to bWX \to b\ell X$. We take $m_t = 170$GeV, $m_{\widetilde{g}} = 190$GeV, $m_{\widetilde{q}} = 350$GeV, $m_{\widetilde{t}_1} = 15$GeV, $m_{\widetilde{Z}_1} = 13$GeV and $\sqrt{s} = 1.8$TeV.

FIG. 3. Contours for $m_{\widetilde{Z}_1} = 13$GeV and $m_{\widetilde{W}_1} = 45$GeV in $(\mu,\, m_{\widetilde{g}})$ plane. We take $\tan\beta = 3$, $f_2 = 2$ and $f_3 = 2.5$.